



Software Diversification for WebAssembly

JAVIER CABRERA-ARTEAGA

Doctoral Thesis in Computer Science
Supervised by
Benoit Baudry and Martin Monperrus

Stockholm, Sweden, March 2024

KTH Royal Institute of Technology
School of Electrical Engineering and Computer Science
Division of Software and Computer Systems
TRITA-EECS-AVL-2020:4 SE-10044 Stockholm
ISBN 100- Sweden

Akademisk avhandling som med tillstånd av Kungl Tekniska högskolan framlägges
till offentlig granskning för avläggande av Teknologie doktorexamen i elektroteknik
i .

© Javier Cabrera-Arteaga , March 7th 2024

Tryck: Universitetsservice US AB

Abstract

WebAssembly, now the fourth officially recognized web language, enables web browsers to port native applications for the Web. Importantly, WebAssembly has evolved into an essential element for backend scenarios such as cloud computing and edge computing. Therefore, WebAssembly finds use in a plethora of applications, including but not limited to, web browsers, blockchain, and cloud computing. Despite the emphasis on security since its design and specification, WebAssembly remains susceptible to various forms of attacks, including memory corruption and side-channels. Furthermore, WebAssembly has been manipulated to disseminate malware, particularly in cases of browser cryptojacking. Interestingly, the predictability of the WebAssembly ecosystem, encompassing its consumers and hosted programs, is remarkably high. Such predictability can amplify the effects of vulnerabilities within these ecosystems. For instance, a defect in a web browser, triggered by a faulty WebAssembly program, could potentially impact millions of users.

This thesis aims to bolster the security within the WebAssembly ecosystem through the introduction of Software Diversification methods and tools. Software Diversification is a strategy designed to augment the costs of exploiting vulnerabilities by making software unpredictable. The unpredictability within ecosystems can be diminished by automatically generating various program variants. These variants strengthen observable properties that are typically used to launch attacks, and in many instances, can completely eliminate such vulnerabilities.

This work introduces three tools: CROW, MEWE, and WASM-MUTATE. Each tool has been specifically designed to tackle a unique facet of Software Diversification. Furthermore, these tools complement each other. We present empirical evidence demonstrating the potential application of our Software Diversification methods to WebAssembly programs in two distinct ways: Offensive and Defensive Software Diversification. Our research into Offensive Software Diversification in WebAssembly unveils potential paths for enhancing the detection of WebAssembly malware. On the other hand, our experiments in Defensive Software Diversification show that WebAssembly programs can be hardened against side-channel attacks, specifically the Spectre attack.

Keywords: WebAssembly, Software Diversification, Side-Channels

Sammanfattning

LIST OF PAPERS

1. ***WebAssembly Diversification for Malware Evasion***
Javier Cabrera-Arteaga, Tim Toady, Martin Monperrus, Benoit Baudry
Computers & Security, Volume 131, 2023, 17 pages
<https://www.sciencedirect.com/science/article/pii/S0167404823002067>
2. ***Wasm-mutate: Fast and Effective Binary Diversification for WebAssembly***
Javier Cabrera-Arteaga, Nicholas Fitzgerald, Martin Monperrus, Benoit Baudry
Submitted to Computers & Security, under revision, 17 pages
<https://arxiv.org/pdf/2309.07638.pdf>
3. ***Multi-Variant Execution at the Edge***
Javier Cabrera-Arteaga, Pierre Laperdrix, Martin Monperrus, Benoit Baudry
Moving Target Defense (MTD 2022), 12 pages
<https://dl.acm.org/doi/abs/10.1145/3560828.3564007>
4. ***CROW: Code Diversification for WebAssembly***
Javier Cabrera-Arteaga, Orestis Floros, Oscar Vera-Pérez, Benoit Baudry, Martin Monperrus
Measurements, Attacks, and Defenses for the Web (MADWeb 2021), 12 pages
<https://doi.org/10.14722/madweb.2021.23004>
5. ***Superoptimization of WebAssembly Bytecode***
Javier Cabrera-Arteaga, Shrinish Donde, Jian Gu, Orestis Floros, Lucas Satabin, Benoit Baudry, Martin Monperrus
Conference Companion of the 4th International Conference on Art, Science, and Engineering of Programming (Programming 2021), MoreVMs, 4 pages
<https://doi.org/10.1145/3397537.3397567>
6. ***Scalable Comparison of JavaScript V8 Bytecode Traces***
Javier Cabrera-Arteaga, Martin Monperrus, Benoit Baudry
11th ACM SIGPLAN International Workshop on Virtual Machines and Intermediate Languages (SPLASH 2019), 10 pages
<https://doi.org/10.1145/3358504.3361228>

ACKNOWLEDGEMENT

TODO W **TODO** O
TODO Jury
TODO C
TODO F

Contents

| | |
|--|------------|
| List of Papers | iii |
| Acknowledgement | iv |
| Contents | 1 |
| | |
| I Thesis | 4 |
| | |
| 1 Introduction | 5 |
| 1.1 Predictability in WebAssembly ecosystems | 7 |
| 1.2 Problems statements | 9 |
| 1.3 Software Diversification | 9 |
| 1.4 Summary of research papers. | 10 |
| | |
| 2 Background and state of the art | 13 |
| 2.1 WebAssembly | 13 |
| 2.1.1 From source code to WebAssembly | 14 |
| 2.1.2 WebAssembly's binary format | 17 |
| 2.1.3 WebAssembly's runtime | 18 |
| 2.1.4 WebAssembly's control-flow | 20 |
| 2.1.5 Security and reliability for WebAssembly | 21 |
| 2.1.6 Open challenges | 22 |
| 2.2 Software diversification | 23 |
| 2.2.1 Automatic generation of software variants | 24 |
| 2.2.2 Equivalence Checking | 26 |
| 2.2.3 Variants deployment. | 27 |
| 2.2.4 Measuring Software Diversification | 28 |
| 2.2.5 Offensive or Defensive assessment of diversification | 30 |

| | | |
|----------|---|-----------|
| 2.3 | Open challenges for Software Diversification | 30 |
| 3 | Automatic Software Diversification for WebAssembly | 32 |
| 3.1 | CROW: Code Randomization of WebAssembly | 33 |
| 3.1.1 | Enumerative synthesis | 34 |
| 3.1.2 | Constant inferring | 35 |
| 3.1.3 | Exemplifying CROW | 36 |
| 3.2 | MEWE: Multi-variant Execution for WebAssembly | 38 |
| 3.2.1 | Multivariant call graph. | 39 |
| 3.2.2 | Exemplifying a Multivariant binary | 39 |
| 3.3 | WASM-MUTATE: Fast and Effective Binary Diversification for WebAssembly | 42 |
| 3.3.1 | WebAssembly Rewriting Rules | 43 |
| 3.3.2 | E-Graphs traversals | 44 |
| 3.3.3 | Exemplifying WASM-MUTATE | 45 |
| 3.4 | Comparing CROW, MEWE, and WASM-MUTATE | 47 |
| 3.4.1 | Security applications | 50 |
| 4 | Assessing Software Diversification for WebAssembly | 52 |
| 4.1 | Offensive Diversification: Malware evasion. | 52 |
| 4.1.1 | Cryptojacking defense evasion | 53 |
| 4.1.2 | Methodology | 54 |
| 4.1.3 | Results | 56 |
| 4.2 | Defensive Diversification: Speculative Side-channel protection . . | 59 |
| 4.2.1 | Threat model: speculative side-channel attacks | 60 |
| 4.2.2 | Methodology | 61 |
| 4.2.3 | Results | 63 |
| 5 | Conclusions and Future Work | 68 |
| 5.1 | Summary of technical contributions | 68 |
| 5.2 | Summary of empirical findings | 69 |
| 5.3 | Future Work | 70 |
| 5.3.1 | Data augmentation for Machine Learning on WebAssembly programs. | 70 |
| 5.3.2 | Improving WebAssembly malware detection via canonicalization | 71 |
| 5.3.3 | Oneshot Diversification | 72 |

| | |
|-----------------|---|
| <i>CONTENTS</i> | 3 |
|-----------------|---|

| | |
|-------------------|-----------|
| References | 73 |
|-------------------|-----------|

| | |
|---------------------------|-----------|
| II Included papers | 88 |
|---------------------------|-----------|

| | |
|---|-----------|
| WebAssembly Diversification for Malware Evasion | 90 |
|---|-----------|

| | |
|--|-----------|
| Wasm-mutate: Fast and Effective Binary Diversification for WebAssembly | 91 |
|--|-----------|

| | |
|--|-----------|
| CROW: Code Diversification for WebAssembly | 92 |
|--|-----------|

| | |
|-------------------------------------|-----------|
| Multi-Variant Execution at the Edge | 93 |
|-------------------------------------|-----------|

| | |
|---|-----------|
| Superoptimization of WebAssembly Bytecode | 94 |
|---|-----------|

| | |
|--|-----------|
| Scalable Comparison of JavaScript V8 Bytecode Traces | 95 |
|--|-----------|

Part I

Thesis